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A HIERARCHICAL AND DYNAMIC LARGE-SCALE RAILWAY-TRACK MODELING SOLUTION FOR HIGH-SPEED TRAIN REAL-TIME VISUAL SIMULATION

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Abstract. *Large-scale railway-track modeling is a key and challenging problem for real-time visual simulation of the high-speed train. The railway-track can generally be described by its central line, whose length and shape vary dramatically between different ones. Therefore, modeling of a large-scale specified railway-track is not a trivial work. A new hierarchical and dynamic modeling framework is proposed to deal with the challenges. Unlike existing top-down approach, this bottom-up solution treats the entire railway-track as the combination of multiple repetitive regularity patterns, namely the elements referred by us. It is an optimized strategy for large model decomposition and is superior in modeling local details. Experiments, including the usage of the proposed method for track assembling and its applications to high-speed train real-time visual simulation, demonstrate the effect and efficiency of our work. Though designed for railway-track modeling, this method can be easily extended to other transportation applications as well.*

Keywords: Modeling, Railway-track, Large-scale scene, Visual simulation

1. **Introduction.** Nowadays, the high-speed railway transportation system has become one of the most important travelling ways in China and aboard. Many researches focus on this rich and state-of-the-art field for the purpose of improving its security, comfortability and speed, which include the computer-aided manufacture [1], driver training [2], track designation [3], aerodynamic noise [4], wireless communications [8], wheel-rail contact analyzing [10], etc. Among these researches, visual simulation of high-speed train plays an importance role in training drivers, demonstration and many other related purposes.

In this paper, we aim to develop a large-scale railway-track modeling method for high-speed train real-time visual simulation. In such simulation, high-speed trains are animated to move along a specific railway-track according to the simulated driving data which can be generated by traction calculation as Li et al. [5] present. Different from cartoon movies, the system should be able to render the scene around 30 frames per second and feedback the user interactions in realtime.

Large-scale railway-tracks are important objects among various scenes which need to be presented in the railway visual simulation. Modeling of a specified railway-track and rendering the scene properly are key and challenging problems. A railway-track can generally be described by its central lines (CL), while the length and shape vary dramatically between different ones in the real world. A most straightforward solution, as mentioned by Pu and Zhang [3], is to construct the models by surface lofting and space array techniques. As an implement of [3], an automatic solution is introduced by Deng et al. [6] using the Openflight API for programming, but their experimental result shows no curved track models. The lofting technique also was adopted by Chen et al. [9] for complex track modeling. Because of the memory limitation, a major drawback of above top-down approaches, which generate a large-scale mesh model once entirely, is that they are time costing and usually suffer from choosing proper strategy to decompose the model. Another drawback lies in the poor efficiency for displaying model details.

Different from methods introduced above, this paper provides a novel bottom-up solution, which considers the entire railway-track as the combination of multiple hierarchical models: the linear and curved ones. Section 2 gives the reasons of this strategy. These hierarchical models will be off-line manually generated (see Section 3) and on-line hierarchically and dynamically assembled (see Section 4) to form an integrated railway-track. Section 5 presents some experimental results and applications. Section 6 concludes this paper.

2. Analysis and Pre-processes.

Inspired by the work of Pauly et al. [7], who mentioned that regular or repeated geometric structures are ubiquitous in both natural and man-made objects, we also find that it is very helpful to adopt the repetitive regularity patterns of tracks for complexity reducing in the modeling processes. Find the repetitive regularity pattern of a large-scale railway-track means to find a way to subdivide them.

As primary inputs, the CL data contain several descriptive properties, such as the type, length and radius for each connected linear or curved components of a railway-track (see Table 1). The track components will be referred to as segments in this work. A large quantity of data analysis reveal that regularity patterns can be found in terms of the radius and length two dimensionally in two steps. In the first step, an integrated railway-track can be divided into segments, which will be grouped by their radius. For example, Table 2 shows the statistical information of a railway-track which is longer than one thousand kilometers, and the segments are categorized into the same class if they are the same in radius. As an exception, all straight segments will be grouped as one category.

Table 1. The original CL and NCL description for a 4 segments composed track

Segment Index	Type	Original CL			NCL		
		Initial (m)	Length (m)	Radius (m)	Initial (m)	Length (m)	Radius (m)
1	Left curve	0	1001	460	0	1000	800
2	Straight	1001	1649	NULL	1000	1650	NULL
3	Right curve	2650	659	3500	2650	650	3500
4	Straight	3309	1270	NULL	3300	1250	NULL

Table 2. Statistics of curved segments in terms of the radius

Category	Radius (m)	Amount	Category	Radius (m)	Amount
Category 1	400	1	Category 6	5500	2
	460	1	Category 7	7000	19
	800	1	Category 8	8000	29
Category 2	2200	1	Category 9	9000	49
	2500	1	Category 10	10000	54
Category 3	3500	1	Category 11	11000	13
Category 4	4000	1	Category 12	12000	21
Category 5	4500	2	Category 13	14000	6

In the second step, segment belonging to the same categories described in the first step can be divided into smaller components which are equal in length. As the result of two steps above, the components identical in both radius and length are repetitive regularity patterns of railway-track and are called elements in this paper.

To further reduce the category of segment and make sure each segment can be represented by a number of element models, the original CL data need to be normalized as NCL (normalized CL). Firstly, the segments with similar radius can be united into one category (e.g., Category 1 in Table 2). In other words, segment with radius R' may be changed to the most approximate radius $R \in \Re$, where $\Re$ is a set of possible radius value of elements. Secondly, the length L' of a segment should be modified to a closest value L which satisfies $L = n \times l$, where n is a positive integer and l is the length of elements. The $\Re$ and l should be preset according to the precision required for the simulation.

3. **Off-line Approaches.** Though a track is of irregular shape, it can be described as a sequence of linear (like the top and bottom inserts in Figure 1(a)) or curved (like the middle insert in Figure 1(a)) segments generally. They can further be divided into multiple elements. Therefore, a railway-track can be viewed as the hierarchical structure as shown in Figure 1(b).

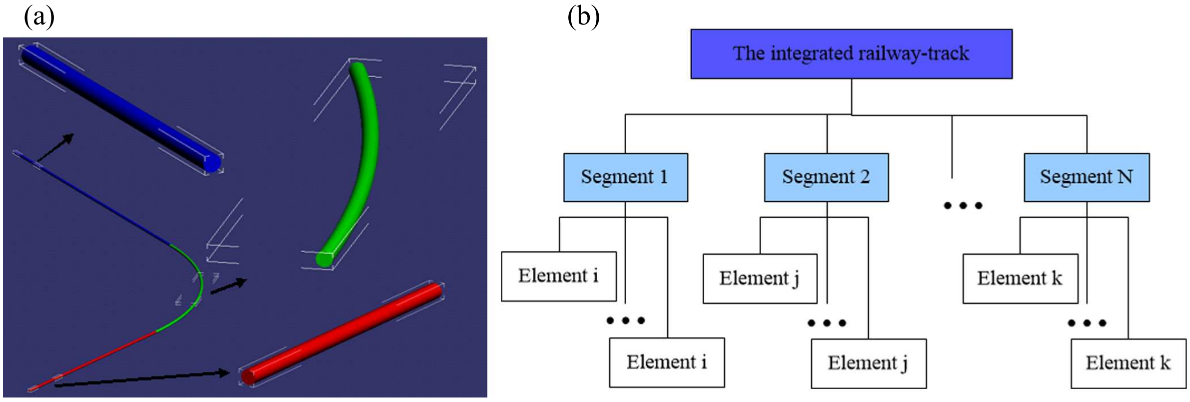

Figure 1. Demonstration of the structure of a track: (a) demonstration of segments and elements of a track, (b) hierarchical structure of an integrated track

In order to hand the element modeling works over to professionals for off-line modeling, the elements should be well defined, as introduced below.

Definition 3.1. *The CL of a curved element should meet that 1) its initial point lies on y-axis and 2) its center locates in the original point.*

Definition 3.2. *The CL of a linear element should meet that 1) its initial point lies on the original point and 2) its orientation parallels to x-axis direction.*

Definition 3.3. *A left curved element should meet that 1) its radius is a positive constant, 2) the direction from initial point to terminal point is counterclockwise and 3) its central angle* $\theta \in (0, 2\pi)$.

Definition 3.4. *A right curved element should meet that 1) its radius is a negative constant, 2) the direction from initial point to terminal point is clockwise and 3) its central angle* $\theta' \in (-2\pi, 0)$.

Figures 2(a) and 2(b) demonstrate the definitions described above. Though, there are two kinds of curved elements, the dual curved elements with opposite radius (as defined in Definitions 3.3 and 3.4) can easily be generated from one to another by mirroring operation.

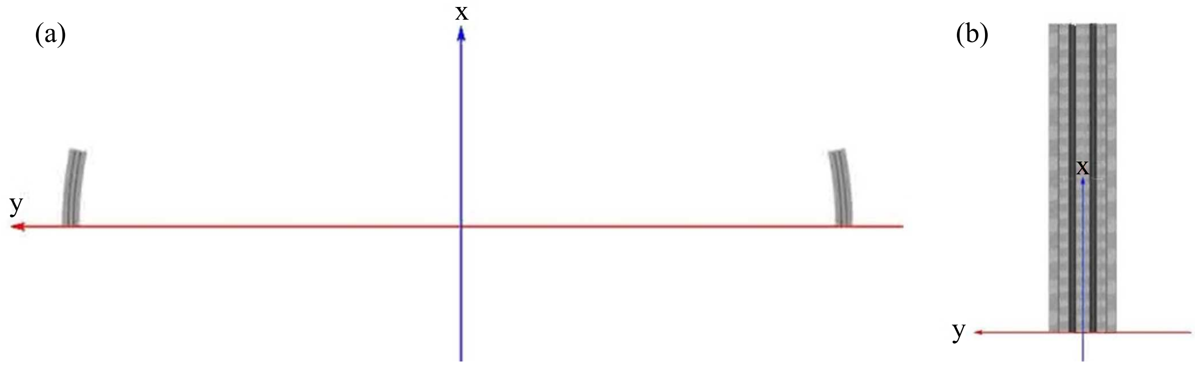

FIGURE 2. Track element designed with 3DS MAX: (a) a top view of the left and right curved elements, (b) a top view of the linear element

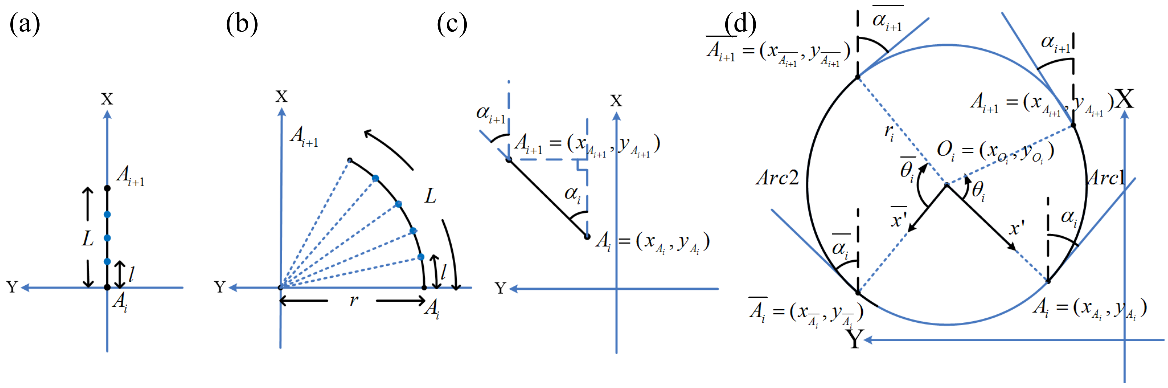

FIGURE 3. The parameters for assembling the (a) linear element, (b) curved element, (c) linear segment and (d) curved segment, respectively

4. **On-line Approaches.** We call the modeling method as a hierarchical and dynamic one, not only because we treat the entire railway-track as a hierarchical structure, but also because the track is dynamically assembled on-line during the animation. Specifically, in the assembling steps, elements are firstly assembled into a segment (see Section 4.1), and then segments are integrated into an integrated track (see Section 4.2). All elements are stored in hard disc statically, while only part of them will be loaded to or removed from the computer memory as required dynamically.

4.1. **Assembling Step 1: from elements to a segment.** In the first step, elements are firstly transformed to form a segment. Let L and l denote the lengths of corresponding segment and element respectively. A linear segment, as demonstrated in Figure 3(a), can be made up of $n = L/l$ linear elements by translation. And the ith $(1 \leq i \leq n)$ element should be translated distance $(i-1) \times l$ in x-axis direction from its initial position. For curved segment shown in Figure 3(b), it can also be made up of $n = L/l$ curved element. As a consequence, the ith $(1 \leq i \leq n)$ element has to rotate $(i-1) \times \theta/n$ degrees from the initial position for the assembling, where $\theta = n \times l/r$, and r denotes the radius.

4.2. **Assembling Step 2: from segments to an integrated track.** After segments have been assembled, their parameters such as coordination, direction fit in the NCL have to be solved in order to restore the original track. Suppose (x_{Ai}, y_{Ai}) is the Cartesian coordinates of a linear segment at the initial point A_i described in NCL, and α_i denotes the direction as demonstrated in Figure 3(c). Then the coordinate (x_{Ai+1}, y_{Ai+1}) and direction α_{i+1} of the consecutive segment at point A_{i+1} should meet Equation (1).

$$\begin{cases} x_{A_{i+1}} = x_{A_i} + L_i \cos(\alpha_i) \\ y_{A_{i+1}} = y_{A_i} + L_i \sin(\alpha_i) \\ \alpha_{i+1} = \alpha_i \end{cases} \tag{1}$$

Curved segment can be easily located by its central coordinate $O_i = (x_{O_i}, y_{O_i})$ and the direction at the initial point. Figure 3(d) denotes both left and right curved segments marked with black arc. Given a left curved segment, let (x_{A_i}, y_{A_i}) and α_i denote the coordinate and direction at initial point A_i respectively, the coordinate (x_{O_i}, y_{O_i}) of the central point O_i and the coordinate $(x_{A_{i+1}}, y_{A_{i+1}})$ of the terminal point A_{i+1} (i.e., the initial point of the consecutive segment) can be solved using Equations (2) and (3). The calculations are carried out in polar coordinates for convenience.

$$\begin{cases} x_{O_i} = x_{A_i} - r_i \sin(\alpha_i) \\ y_{O_i} = y_{A_i} + r_i \cos(\alpha_i) \end{cases} \tag{2}$$

$$\begin{cases} x_{A_{i+1}} = x_{O_i} + r_i \sin(\alpha_i + \theta_i) \\ y_{A_{i+1}} = y_{O_i} - r_i \cos(\alpha_i + \theta_i) \\ \alpha_{i+1} = \alpha_i + \theta_i \end{cases} \tag{3}$$

where $\theta_i = L_i/r_i$, L_i and r_i are length and radius. Situations for right curved segment can also comply with Equations (2) and (3), only if the sign of the radius is negative, as defined in Definition 3.4.

5. **Results and Applications.** To validate the proposed method, a track composed of four connected segments as described in Table 1 is firstly generated. And element models as demonstrated in Figure 2, whose length $l = 50$m, are used in this experiment to construct the track. Result depicted in Figure 4 shows that the track with connected linear and curved components can be assembled smoothly in our method.

Figure 4. Experiment 1: visualization results of a track whose CL data are described in Table 1.

In the simulation, high-speed trains are supposed to move along a specific rail. In order to realize it, the positions and directions of uniformly distributed discrete rail points can be generated based on NCL by an approach similar to parameters computation introduced above. And the train models can be located accordingly. In Figure 5, we use small spheres to indicate the discrete points and test the method. As we can see, the spheres are correctly placed with the computation method, which will be the train models.

Finally, the proposed method is implemented in a high-speed train visual simulation system. In this case, models such as ground, mountains, trees, houses and sky dome are added to the scene. Users are allowed to interact with the system, such as viewing the rendering scene in different views, as illustrated in Figure 6.

Figure 5. Experiment 2: testing of the parameter computation method for train model locating by placing small spheres at each discrete rail point

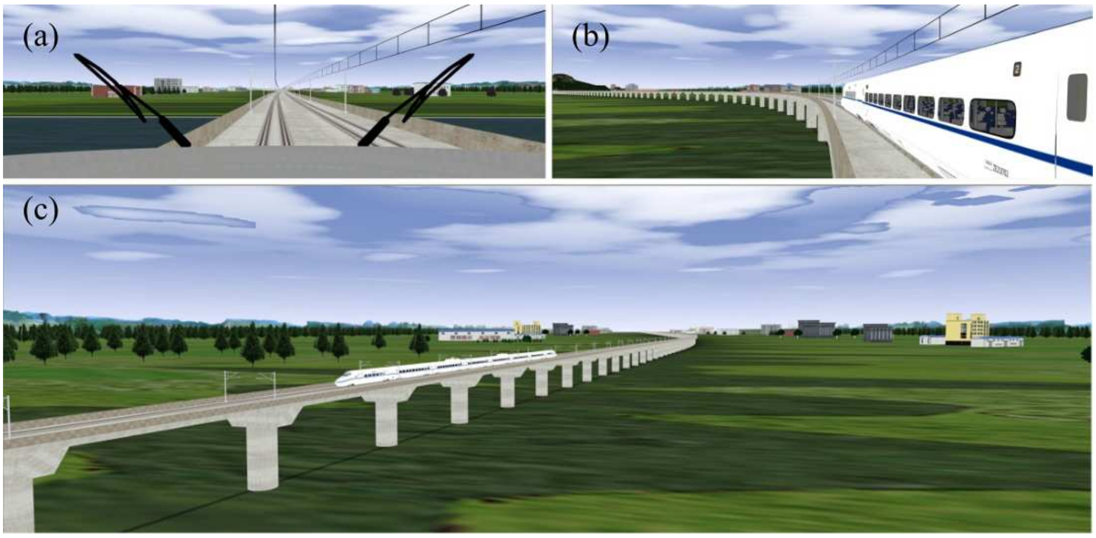

Figure 6. Experiment 3: applying the hierarchical and dynamic track modeling method in a high-speed train visual simulation system: (a) a perspective view in the cab, (b) a left outboard view whose viewpoint moves along the train, (c) a right outboard view whose viewpoint is fixed outside of the train

6. **Conclusions.** In this paper, a hierarchical and dynamic framework for modeling large-scale railway-track described with its CL is introduced. The core idea of the proposed framework is finding and using the repetitive regularity patterns of railway-track. Several benefits follow from this framework. First, this bottom-up strategy, which bases on element models, provides a new way of simplification in track modeling. Second, the method is very easy to realize, and is competent for real-time rendering and user interactions. Finally, this new method is robust for tracks with different scales and shapes, as long as the CL is specified. Though designed for railway-track modeling, this method can be easily extended to other transportation applications as well.

This work assumes that the height of track is a constant, because the variation of height would sharply increase the complexity of element models. Deformations for element models may be a feasible direction to solve this problem. Thus, modeling track with slope will be one of our future works.

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